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ORIGINAL RESEARCH

Integrated use of compost and lime enhances soil properties and wheat (*Triticum aestivum* L.) yield in acidic soils of Northwestern Ethiopia

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Abstract

Purpose Soil acidity and nutrients deficiency are the major constraints causing low crop yield and food insecurity in the highlands of Ethiopia. A field experiment was conducted in northwestern Ethiopia during 2018 and 2019 cropping seasons to study effects of compost and lime application on soil properties and wheat yield.

Method The treatments consisted of three compost levels (0, 3 and 6 t ha^{-1}) and three lime rates (0, 1 and 2 t ha^{-1}) arranged in a randomized complete block design with three replications. Before planting and after harvest, soil samples were collected from each experimental plot to analyze soil properties.

Results Combination of lime and compost significantly ($p<0.05$) increased soil pH, soil organic carbon, total nitrogen, available phosphorus and exchangeable base cations. In contrast, exchangeable acidity and aluminum levels decreased substantially compared to individual application of amendments. Compared to the control, application of 2 t ha^{-1} lime, 6 t ha^{-1} compost alone and their combination increased wheat grain yield by 24.6%, 42% and 97.5%, respectively. Besides, the combined application of compost and lime provided the highest net benefit (1915.90 US$ ha^{-1}), which was noticeably greater than the control (1034.44 US$ ha^{-1}).

Conclusion The application of lime and compost in combination is an effective option to curb soil acidity while enhancing soil nutrients availability and crop yields at lower input costs. However, to determine the application frequency, long-term effects of compost and lime in combination on acidic soil properties and crop yield need to be investigated through further research.

Keywords Compost, Crop yield, Liming, Soil acidity, Soil fertility

Introduction

Soil acidity is among the major constraints leading to nutrients deficiency, low crop yields and food insecurity in Sub-Saharan Africa (SSA) (Elias 2016; FAO and ITPS 2015). About 43% of cultivated land in Ethiopian highlands is affected by soil acidity (Ethiosis 2016). Toxic levels of Al, Mn, and Fe, high P fixation and limited nutrients availability are the key constraints hampering crop productivity in acidic soils (Kochian et al.

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2004). Besides, Al toxicity severely limits crop production by impairing root growth and inhibiting lateral root formation, thereby restricting nutrients and water uptake by plants (Baquy et al. 2017).

Wheat (*Triticum aestivum L.)* is one of the major cereal crops widely grown for its vital role in nutrition, income and food security. Wheat covers an estimated area of 1.7 million ha, with 4.6 million tons of total annual production. However, wheat productivity is very low, with a national average yield of 2.2 t ha^{-1}, far below yields obtained from the research stations (5 t ha^{-1}) (Tamene et al. 2017). Soil fertility decline due to soil acidity is one of the main constraints causing low crop yields in the Ethiopian highlands (Elias et al. 2020).

Mineral fertilizers are widely applied to alleviate nutrients depletion and boost crop yields in Ethiopia (Elias et al. 2019; Yihenew 2015). However, resource-poor farmers cannot apply the recommended rates of mineral fertilizers due to its high cost (Tamene et al. 2017). Besides, continued use of mineral fertilizers is not an environmental-friendly and sustainable practice as it can cause soil health degradations such as soil acidification, depletion of soil organic matter and other nutrients that are not provided by these fertilizers (Srinivasan et al. 2014; Mtangadura et al. 2017; Al-mansour et al. 2018).

Previous studies showed that liming is the most effective method for alleviating soil acidity and enhancing nutrient availability (Bekele et al. 2018; Liu et al. 2020; Moreira et al. 2015). Lime addition increases soil pH, decreases Al^{3+} toxicity and P fixation (Fekadu et al. 2018; Melese et al. 2015). Besides, liming improves soil microbial activity, increasing organic matter decomposition and releasing essential nutrients such as P, N, K, Ca and Mg (Bossolania et al. 2020; Mkhonza et al. 2020) and increasing crop yields (Demil et al. 2020). However, smallholder farmers cannot afford to buy a sufficient amount of lime due to its high cost and limited supply. Hence, viable and sustainable options are urgently needed for smallholder farmers to mitigate soil acidity, improve nutrient availability and crop yields.

Organic amendments have played a vital role in enhancing soil properties (Mamuye et al. 2021; Opala et al. 2012) and crop yields (Al-mansour et al. 2018; Jahiruddin et al. 2019; Vishwanath et al. 2020). However, the effect of organic inputs on soil acidity has not been clearly understood.

For instance, Moreira et al. (2015) and Ywih et al. (2014) reported that organic amendments increase soil pH and decrease exchangeable acidity and exchangeable Al^{3+} contents of the soil. On the contrary, Adekiya et al. (2020) and Mahmood et al. (2017) found that the addition of different types of manures decrease soil pH and increase soil acidity, which could be attributed to the release of organic acids during the decomposition of applied manures may consume protons and thereby decreasing soil pH. These contradicting views have not been settled yet, and limited research has been carried out to explore such issues in Ethiopian highlands. Moreover, organic amendments alone cannot replenish depleted nutrients due to limited organic inputs, bulkiness and inadequate nutrient contents. Integrated use of organic and inorganic amendments has become the most effective strategy in improving soil health and crop yields (Fekadu et al. 2018; Bekele et al. 2018; Vishwanath et al. 2020). However, previous studies rely too much on incubation trials and pot experiments with limited field verification (Bekele et al. 2018; Melese et al. 2015; Opala et al. 2012). Moreover, the adoption of compost and lime in combination to alleviate soil acidity and enhance crop yields is poor in the Ethiopian highlands. Determining the effects of compost and lime in combination on soil properties and crop yield is vital to develop optimal rates and convince farmers to integrate the soil fertility management approach. Therefore, the objective of this study was to evaluate the effects of the combined application of lime and compost on acidic soil properties and wheat yields in the highlands of Northwestern Ethiopia.

Materials and methods

Description of the study area

The field experiment was conducted during the 2018 and 2019 cropping seasons in Sahirna village of Farta district, Northwestern Ethiopia (Fig 1). The study area is geographically placed between 11°45’34’’ to 11°48’25’’ N latitude and 38°4’ 3’’ to 38°6’14’ E longitude. The altitude varies between 1900 and 4035 meters above sea level. Regarding the topography, 45% is a gentle slope, while 29 and 26% are characterized by flat and steep slope lands, respectively. Based on 20 years (2000-2019) climatic data collected from the Meteorological Office, the minimum, maximum and average temperatures are 9.52, 22.95 and 15.8˚C, respectively.

In addition, the study area has mean annual precipitation of 1482.30 mm. Rainfall distribution of the area is unimodal, and the main rainy season extends from May to September (Fig 2). Based on the information obtained from Farta District Agricultural Office (unpublished), land use types of the district consist of arable land (64.7%), grazing (10.2%), forests and shrubs (0.6%), settlement (7.8%) and wetlands (16%). The farming practice is described by a subsistence crop-livestock mixed system where barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), tef (*Eragrostis tef Zucc.* Trotter), potato (*Solanum tuberosum*) and faba bean (*Vicia faba* L.) are the main grown crops.

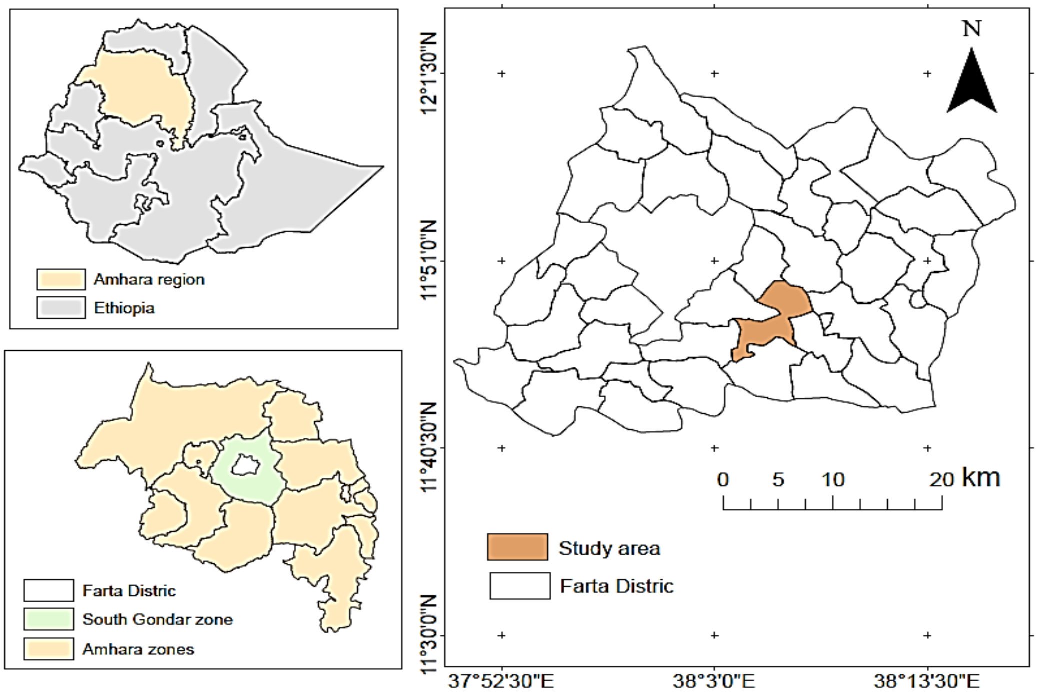

Fig. 1 Location map of the study area

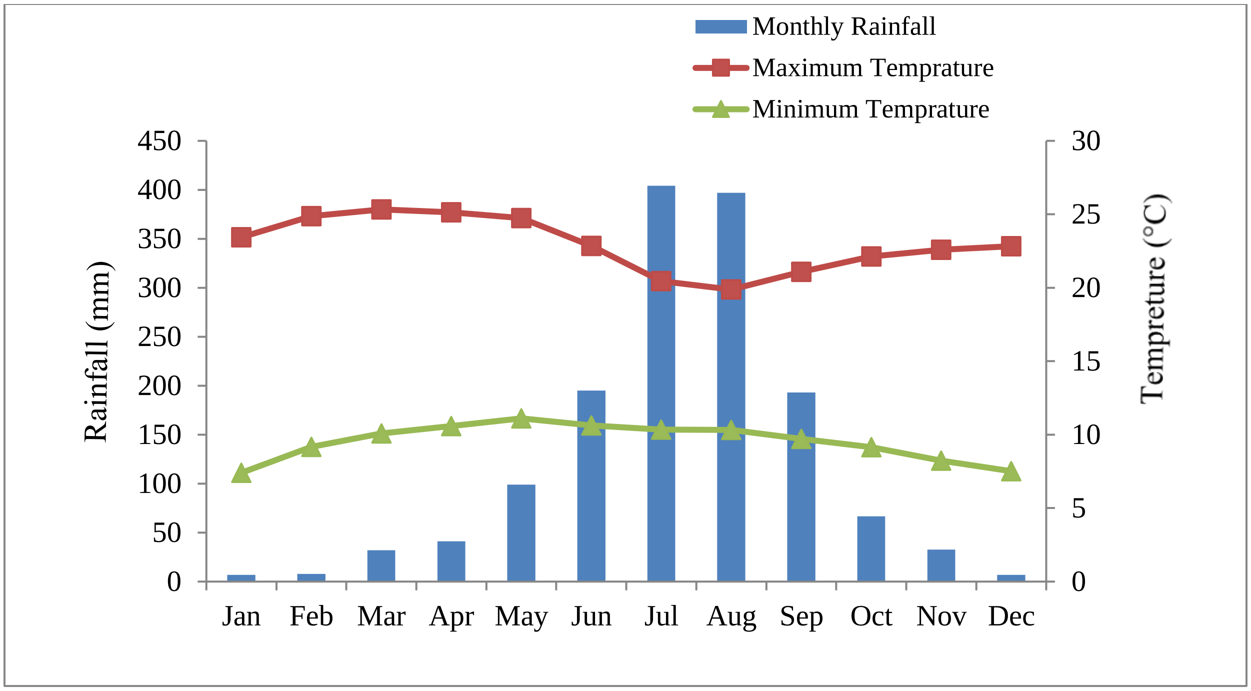

Fig. 2 Rainfall and temperature distributions of the study area

Experimental treatments and design

The treatments consisted of three compost rates (0, 3 and 6 t ha^{-1}) and three lime levels (0, 1 and 2 t ha^{-1}). Besides, all plots were uniformly treated with 75 kg ha^{-1} blend NPSB (18.1:36.1:6.7:0.71) and 150 kg ha^{-1} urea (75% recommended mineral fertilizer rates). The field experiment was arranged in a randomized complete block design with three replications.

The gross plot size was 2.4 m x 2.5 m (6 m^2), while the net plot size was 1.6 m x 1.7 m (2.72 m^2). The adjacent blocks, plots and rows were separated by 1 m, 0.5 m, and 0.2 m, respectively. The experimental site was plowed three times before wheat sowing as per the conventional practice in the study area. Improved bread wheat variety named '*Tay*' was used as a test crop. The full dose of NPSB and half urea were incorporated during planting, while the remaining half dose of urea was applied at the tillering stage of wheat. Agricultural lime used for this experiment has 94% calcium carbonate equivalence made by the Dejen limestone crushing factory. Lime and compost amendments were applied once alone at the start of the field experiment, while mineral fertilizers were incorporated during each cropping season. The lime rate was estimated using the equation below (1) (Demissie et al. 2017):

$$LR \quad = \frac{\text{Exch.Ac X BD } X \text{ Depth (m) } X\ 10^4\text{m}^2}{2} \qquad (1)$$

Where LR = Lime requirement ($CaCO_3$ kg ha^{-1}); Exch. Ac is exchangeable acidity of the soil (cmol $(_+)$ kg^{-1}); BD is bulk density of the soil (g cm^{-3}), and depth is the depth of the plough layer (0.15 m).

Compost preparation

Compost prepared from locally available materials including crop residues, animal manures, green leaves and ash was used for this field experiment. For preparing compost, small pit with a volume of 1m^3 was dug. Then, the pit was filled with composting materials in five layers as follows. Initially, a maize straw was chopped and piled up to 20 cm layer. Second, a mixture of wheat and barley straw was incorporated up to 30 cm thickness.

Third, animal manure was piled up to 3 cm thickness on top of which 2 kg ash material was spread. Fourth, green materials collected from leguminous shrubs and trees were added up to 25 cm thickness. The fifth layer composed of garden topsoil weighing up to 3 kg. The materials in the pit were overturned every 21 days to allow air circulation until the compost is well matured.

Moreover, to evaluate the chemical characteristics (Table 2), compost sample was collected, prepared and analyzed following the same procedures used for the soil analysis. Similarly, to determine the moisture content, compost sample was taken and oven dried at 105 °C for 24 hours until it comes to a constant weight. After deducting the moisture content, fresh compost measured on dry weight basis was applied three weeks before sowing.

Soil sample collection and analysis

Soil samples were collected from 0-20 cm depth before sowing and after completion of the field experiment in each treatment. The collected soil samples were air-dried, crushed and sieved with a 2 mm diameter screen sieve to analyze soil pH, exchangeable aluminium, available phosphorus, exchangeable bases, and CEC. In addition, soil samples were further passed in a 0.5 mm sieve to determine soil organic carbon and total nitrogen. Based on the standard procedures, the collected soil samples were tested at Amhara Design and Supervision Works Enterprise soil laboratory center.

The particle size distribution was analyzed with the Hydrometer technique (Bouyoucos 1962). Soil bulk density (SBD) was measured with a core sampler (Blake and Hartge 1986). Soil pH was determined using a digital PHS-3E pH meter in 1:2.5 soil-water extract (Van Reeuwijk 2002). Total nitrogen (TN) was analyzed by micro-Kjedahl method (Bremner and Mulvaney 1982). Soil organic carbon (SOC) was determined using the wet digestion method (Bremner and Mulvaney 1982). Available phosphorus (AP) was analyzed using the $NaHCO_3$ extraction method (Olsen et al. 1954). Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+ and Na^+) and available sulfur (AS) were determined using the Mehlich-3 method (Mehlich 1984). Cation exchange capacity (CEC) was determined following extraction of a soil sample by 1 M ammonium acetate (NH_4OAC) (Van Reeuwijk 2002). Exchangeable acidity was determined by 1 M KCl extraction and with 0.02 M NaOH titration method as outlined in Rowell (2014).

Agronomic data collection

Plant height was measured from the soil surface to the tassel base of randomly selected wheat plants. Total biomass yield of wheat was measured using graduated balance following complete sun-drying of sample plants taken from each net plot area. Initially, the grain yield was threshed, cleaned from straw and debris, and then weighed using a sensitive electrical balance. Grain yield was adjusted to 12.5% moisture content and converted to a hectare basis (t ha^{-1}). Straw yield was quantified by subtracting grain yield from biomass yield.

Cost-benefit analysis

Partial budget analysis was performed according to CIMMYT methodology (CIMMYT 1988) to determine the costs and benefits of treatments. The local costs of urea fertilizer (15.20 Birr kg^{-1}), NPSB (15.40 Birr kg^{-1}), lime (2 Birr kg^{-1}). Labor cost for compost making was estimated according to World Food Program, where standards of 660 Birr and 1320 Birr for 3 and 6 t ha^{-1}, respectively, were used to estimate total variable costs. Grain and straw yields were reduced by 10% to consider variations between farmers and research fields. Gross field benefits were quantified by multiplying wheat grain and straw yields with their present costs (15.80 and 1.0 Birr kg^{-1}, respectively). The net benefit was estimated by deducting total variable costs from gross benefit. Then, treatments were arranged in increasing order of total variable costs. Dominated treatments were removed from a marginal rate of return (MRR) analysis. Lastly, MRR was estimated using the equation (2) stated below (CIMMYT 1988):

$$\mathrm{MRR}(\%) = \frac{\text{Marginal increase in gross margin}}{\text{Marginal increase in variable cost}} \times 100 \qquad (2)$$

Statistical analysis

To determine the effects of treatments on soil properties and wheat yields, the collected soil and crop data were subjected to analysis of variance (ANOVA) using a general linear model (GLM) procedure of Statistical Analysis System (SAS) software version 9.2 (SAS Institute 2008). When the ANOVA revealed significant differences between treatments, mean separation was performed using Tukey's test at $p<0.05$.

Results and discussion

Soil and compost characteristics before the experiment

Results showed that the textural class of the soil is clay loam, having an optimum bulk density value (1.26 g cm^{-3}) (Weil and Brady 2016). According to Ethiosis (2016), the study soil was strongly acidic (5.01), had high exchangeable acidity and aluminium (2.17 and 1.33 (cmol $_{(+)}$ kg^{-1}), respectively). Moreover, the content of SOC (1.94%) was very low (Landon 1991), who rated as very low (< 2), low (2-4), medium (4-10), and high (10-20). Table 1 shows that the TN (0.13%), AP (7.45 mg kg^{-1}) and AS (12.29 mg kg^{-1}) were found in low ranges (Landon 1991). Similarly, the concentrations of exchangeable Ca^{2+}, Mg^{2+} and CEC were found in medium status, while the exchangeable K^{+} and Na^{+} were fell within the low and very low ranges, respectively (FAO 2006).

Table 1 Initial soil characteristics before the experiment

Soil parameters	Value
Physical properties	
Sand (%)	23.60
Silt (%)	35.10
Clay (%)	41.30
Textural Class	Clay loam
SBD (g cm^{-3})	1.26
Chemical properties	
Exch. Ac (cmol $_{(+)}$ kg^{-1})	2.17
Exch. Al (cmol $_{(+)}$ kg^{-1})	1.33
Soil pH (water: soil, 1:2.5)	5.01
SOC (%)	1.94
TN (%)	0.13
AP (mg kg^{-1})	7.45
AS (mg kg^{-1})	12.28
Ca^{2+} (cmol $_{(+)}$ kg^{-1})	8.30
Mg^{2+} (cmol $_{(+)}$ kg^{-1})	1.51
K^{+} (cmol $_{(+)}$ kg^{-1})	0.27
Na^{+} (cmol $_{(+)}$ kg^{-1})	0.08
CEC (cmol $_{(+)}$ kg^{-1})	21.82

SBD, soil bulk density; soil pH, soil reaction; Exch. Ac, exchangeable acidity; Exch. Al, exchangeable aluminium; SOC, soil organic carbon; TN, total nitrogen; AP, available phosphorus; AS, available sulphur; Ca^{2+}, Mg^{2+}, K^{+} and Na^{+} are exchangeable Calcium; Magnesium; Potassium and Sodium respectively; CEC, cation exchange capacity

Table 2 shows that the compost applied in this field experiment had a pH of 7.16, OC and TN (11.23 and 0.86%, respectively), AP and AS (295.32 and 517.30 mg kg^{-1}, respectively). The exchangeable Ca^{2+}, Mg^{2+}, K^{+}, Na^{+} and CEC contents were 24.58, 10.07, 0.12 and 0.36 and 39.35 cmol $_{(+)}$ kg^{-1}, respectively. Overall, the results exhibited that compost has good quality and it is a potential nutrients source (Table 2).

Table 2 Compost characteristics before the experiment

Parameter	pH (H_2O)	OC (%)	TN (%)	AP (mg kg^{-1})	AS (mg kg^{-1})	Exchangeable bases (cmol($_+$) kg^{-1})				CEC (cmol($_+$) kg^{-1})
						Ca	Mg	K	Na	
Values	7.16	11.23	0.96	295.3	517.3	24.6	10.07	0.12	0.36	39.35

pH, soil reaction; OC, organic carbon; TN, total nitrogen; AP, available phosphorus; AS, available sulphur; Ca^{2+}, Mg^{2+}, K^+ and Na^+ are exchangeable Calcium; Magnesium; Potassium and Sodium respectively; CEC, cation exchange capacity

Effects of compost and lime combination on soil properties

Results showed that lime and compost application either alone or in combination significantly ($p<0.05$) influenced soil pH and exchangeable Al^{3+} contents (Table **3**). Soil pH increased, while exchangeable acidity and Al levels reduced with increasing compost and lime rates. However, liming was more effective in increasing soil pH, reducing exchangeable acidity and Al^{3+} than sole compost treatments. The mean results of two seasons indicated that the highest soil pH (6.12), lowest exchangeable acidity (0.44 cmol($_+$) kg^{-1}) and exchangeable Al (0.11 cmol($_+$) kg^{-1}) were achieved under plots treated with 2 t ha^{-1} lime and 6 t ha^{-1} compost in combination. On the contrary, the lowest soil pH (4.88), highest exchangeable acidity (2.28 cmol($_+$) kg^{-1}) and Al (1.40 cmol($_+$) kg^{-1}) were observed under the control plots. In the present study, plots amended with 6 t ha^{-1} compost, 2 t ha^{-1} lime alone and their combinations increased soil pH by 9, 14.8 and 25.4%, respectively, compared to the control. On the other hand, the addition of 6 t ha^{-1} compost, 2 t ha^{-1} lime alone and their combination reduced exchangeable acidity by 27.6, 55.7 and 80.7%, respectively. Besides, treatments that received 6 t ha^{-1} compost, 2 t lime ha^{-1} and their combination reduced exchangeable Al^{3+} by 42.6, 65.2 and 92.2%, respectively, compared to the control.

The increase in soil pH, reduction of exchangeable acidity, and Al^{3+} with the addition of compost and lime alone and together could be attributed to greater concentrations of exchangeable cations that can exchange H^+, $Al^{3+,}$ and Fe^{3+} on the surfaces of the soil (Jahiruddin et al. 2019). Our result is in line with Bossolania et al. (2020); Henk et al. (2019) and (Jiangzhou et al. (2020), who reported that liming increased soil pH, reduced exchangeable acidity and Al^{3+}. Besides, humic materials like carboxyl and phenolic compounds produced through compost decomposition might help to precipitate Fe^{3+} and Al^{3+} as Fe and Al hydroxides, which ultimately may have lowered soil acidity (Moreira et al. 2015; Mtangadura et al. 2017). On the other hand, reduction of soil pH increased exchangeable acidity, and Al levels under plots treated with chemical fertilizers alone can be associated with an increase in hydrogen ions (H^+) owing to rapid nitrification of mineral fertilizers (Singh et al. 2017) and loss of exchangeable bases (Adekiya et al. 2020).

The application of lime and compost individually and in combination significantly ($p<0.05$) increased the status of major soil nutrients (Table 4).

The average results revealed that the highest AP (14.10 mg kg^{-1}), SOC (2.79%) and TN (0.26%) were recorded in plots amended with 6 t ha^{-1} compost and 2 t ha^{-1} lime in combination. Compared to the control, sole rates of 2 t ha^{-1} lime, 6 t ha^{-1} compost and their combination notably increased soil AP contents by 40.5, 67.1 and 92.4%, respectively. Besides, the SOC content was 14.8, 33.5 and 37.4% higher with applying 2 t ha^{-1} lime, 6 t ha^{-1} compost separately and their combinations, respectively. Compared to the control, the same treatments also increased TN content by 28.6, 64.3 and 85.7%, respectively.

Table 3 Effects of combined use of lime and compost on acidity indices of the experimental soil

Lime (t ha^{-1})	Compost (t ha^{-1})	Soil pH (water: soil, 1:2.5)			Exch. Ac (cmol $_{(+)}$ kg^{-1})			Exch. Al^{3+} (cmol $_{(+)}$ kg^{-1})		
		2018	2019	Average	2018	2019	Average	2018	2019	Average
0	0	4.94^{g}	4.82^{f}	4.88^{f}	2.24^{a}	2.32^{a}	2.28^{a}	1.37^{a}	1.44^{a}	1.41^{a}
	3	5.10^{fg}	5.20^{e}	5.15^{e}	2.19^{a}	1.98^{b}	2.09^{b}	1.26^{a}	1.13^{b}	1.20^{b}
	6	5.25^{ef}	5.38^{de}	5.32^{de}	1.74^{bc}	1.55^{cd}	1.65^{cd}	0.85^{b}	0.76^{c}	0.81^{cd}
1	0	5.28^{de}	5.39^{d}	5.33^{d}	1.81^{b}	1.62^{c}	1.72^{c}	0.90^{b}	0.79^{c}	0.85^{c}
	3	5.43^{cd}	5.50^{cd}	5.47^{cd}	1.58^{cd}	1.42^{d}	1.50^{de}	0.82^{b}	0.68^{c}	0.75^{c}
	6	5.46^{c}	5.58^{c}	5.52^{c}	1.48^{d}	1.24^{e}	1.36^{e}	0.50^{c}	0.42^{e}	0.46^{d}
2	0	5.54^{c}	5.67^{bc}	5.60^{bc}	1.12^{e}	0.89^{f}	1.01^{f}	0.53^{c}	0.45^{d}	0.49^{d}
	3	5.70^{b}	5.81^{b}	5.76^{b}	0.93^{f}	0.76^{f}	0.85^{f}	0.29^{d}	0.20^{e}	0.25^{e}
	6	6.08^{a}	6.16^{a}	6.12^{a}	0.51^{g}	0.36^{g}	0.44^{g}	0.14^{e}	0.08^{e}	0.11^{f}
P-value		0.040	0.020	0.038	0.028	0.017	0.048	0.047	0.011	0.015
CV (%)		1.81	1.84	1.75	6.30	6.88	6.41	9.40	11.75	9.33

Exch. Ac, exchangeable acidity; Exch. Al^{3+}, exchangeable aluminium; CV, coefficient of variation. Based on Tukey's test, the means followed by the same letters within the same column are not significantly different at $p < 0.05$.

The increment of AP under treatments that received lime and compost in conjunction could be consistent with increased soil pH, decreased exchangeable Al^{3+} and thereby reduced P fixation (Fekadu et al. 2018; Melese et al. 2015). Bekele et al. (2018) also indicated that compost and lime in combination improved microbial activities resulting in better decomposition of compost and improved soil AP. Besides, the addition of organic amendments increased soil AP status might be due to the release of organic acids that bind Al and Fe, thereby reducing P fixation and increasing its availability (Edwards et al. 2016). The increase in SOC due to individual or combined application of treatments may be related to greater crop and root residues (Bossolania et al. 2020). Besides, the higher concentration of SOC observed in compost and integrated amendments can be related to the direct supply of carbon from compost (Zhang et al. 2020). In line with our result, Bekele et al. (2018) also exhibited that integrated use of 4 t ha^{-1} lime and 7.5 t ha^{-1} vermicompost provided the highest content of SOC (4.1%). Bedada et al. (2014) also reported application of organic inputs only or integrated with inorganic fertilizer significantly improved SOC contents.

Similarly, an increase in total N levels from compost and combined treatments might be related to the optimal N content of applied compost (Table 2). Vishwanath et al. (2020) also reported that manure and lime application increased TN contents over the control due to better roots biomass and soil organic matter build-up. Our result concord with Bekele et al. (2018), who found that the highest TN (0.29%) was obtained under integrated use of 4 t ha^{-1} lime and 7.5 t ha^{-1} vermicompost.

However, our finding contradicts with Henk et al. (2019), who reported lower TN from lime amended plots as liming enhances mineralization of organic N and releases available N, which may be utilized by plants or exposed for loss. Our results revealed that the application of lime and compost significantly ($p<0.05$) influenced exchangeable Ca and CEC (Table **5**). However, exchangeable Mg and K did not show significant variation with the application of treatments. The average results indicated that the highest exchangeable Ca (12.78), Mg (2.18) and CEC (32.09) cmol $_{(+)}$ kg^{-1} were recorded from the highest doses of compost and lime combination. Soil exchangeable Ca was 27.3, 40.4 and 60.3% higher due to incorporation of 6 t ha^{-1} compost, 2 t ha^{-1} lime alone and together, respectively, compared to the control plots. The same treatments increased the CEC of the soil by 24.9, 28 and 61.2%, respectively, compared to the control.

Table 4 Effects of treatments on available phosphorus, soil organic carbon and total nitrogen

Lime (t ha^{-1})	Compost (t ha^{-1})	Available P (mg kg^{-1})			Soil Organic Carbon (%)			Total Nitrogen (%)		
		2018	2019	Average	2018	2019	Average	2018	2019	Average
0	0	7.39	7.26^{g}	7.33^{g}	1.97^{g}	2.09^{e}	2.03^{e}	0.13^{g}	0.15^{e}	0.14^{e}
	3	10.55	10.80^{e}	10.68^{e}	2.50^{cd}	2.60^{bc}	2.55^{bc}	0.20^{de}	0.22^{c}	0.21^{c}
	6	12.08	12.41^{c}	12.25^{c}	2.65^{ab}	2.76^{a}	2.71^{a}	0.22^{bc}	0.24^{b}	0.23^{b}
1	0	8.07	8.29^{f}	8.18^{f}	2.14^{f}	2.25^{d}	2.20^{d}	0.14^{g}	0.15^{e}	0.15^{e}
	3	10.78	11.22^{de}	11.00^{de}	2.42^{de}	2.54^{c}	2.48^{c}	0.19^{e}	0.21^{c}	0.21^{c}
	6	12.83	13.28^{b}	13.06^{b}	2.58^{bc}	2.71^{ab}	2.65^{ab}	0.24^{ba}	0.25^{a}	0.25^{a}
2	0	10.14	10.45^{e}	10.30^{e}	2.28^{ef}	2.38^{d}	2.33^{d}	0.17^{f}	0.19^{d}	0.18^{d}
	3	11.60	11.96^{cd}	11.78^{cd}	2.46^{cd}	2.57^{bc}	2.52^{bc}	0.21^{cd}	0.24^{b}	0.23^{b}
	6	13.90	14.30^{a}	14.10^{a}	2.74^{a}	2.83^{a}	2.79^{a}	0.25^{a}	0.26^{a}	0.26^{a}
P-value		0.053	0.020	0.030	0.031	0.038	0.030	0.048	0.036	0.027
CV (%)		4.24	4.18	4.19	3.60	3.27	3.40	4.06	3.58	3.41

CV=, coefficient of variation. Means followed by the same letters within a column are not significantly different at $p < 0.05$, based on Tukey's test.

The improved exchangeable cations in compost and combined treatments may be associated with better contents of exchangeable bases from the applied compost (Table 2). Besides, higher concentrations of exchangeable cations from lime-compost combinations could be ascribed to the increment of soil organic matter that can retain and provide essential nutrients (Bedada et al. 2014). Our result is in line with Bossolania et al. (2020), who reported that liming increased exchangeable Ca^{2+}, Mg^{2+} and K^{+} contents because lime serves as a cementing agent, increasing soil aggregation and retaining basic nutrients (Auler et al. 2019).

Similarly, the increased CEC values from plots amended with lime and compost alone and together could be attributed to raised soil pH and better concentrations of basic cations (Moreira et al. 2015). Moreover, the CEC increment from combined amendments could be related to better soil organic matter build-up that increases the surface area and negative charges, which improves the retention of basic nutrients (Ali et al. 2018; Vishwanath et al. 2020). On the contrary, the decrease in CEC under plots that received chemical fertilizers alone might be due to the decrease in soil pH and loss of basic cations (Singh et al. 2017).

Table 5 Effects of treatments on exchangeable cations and cation exchange capacity

Lime (t ha^{-1})	Compost (t ha^{-1})	Exchangeable cations (cmol $(_{+})$ kg^{-1})									CEC (cmol $(_{+})$ kg^{-1})		
		Ca^{2+}			Mg^{2+}			K^{+}					
		2018	2019	Mean	2018	2019	Mean	2018	2019	Mean	2018	2019	Mean
0	0	8.04^{f}	7.90^{f}	7.97^{g}	1.28^{f}	1.23	1.26^{f}	0.20	0.17	0.19	20.04	19.78^{g}	19.91^{f}
	3	8.39^{ef}	8.85^{e}	8.62^{f}	1.51^{cd}	1.55	1.53^{de}	0.28	0.33	0.30	21.70	22.04^{f}	21.87^{e}
	6	9.82^{d}	10.47^{c}	10.15^{d}	1.77^{c}	1.84	1.81^{b}	0.41	0.48^{c}	0.45	24.67	25.06^{cde}	24.87^{cd}
1	0	8.94^{e}	9.72^{d}	9.33^{e}	1.35^{ef}	1.39	1.37^{ef}	0.21	0.25	0.23	23.40	23.72^{ef}	23.56^{de}
	3	10.13^{d}	10.81^{c}	10.45^{d}	1.55^{c}	1.62	1.59^{c}	0.29	0.35	0.31	23.48	23.90^{de}	23.69^{d}
	6	12.09^{ab}	12.80^{a}	12.44^{a}	2.03^{a}	2.13	2.08^{a}	0.45	0.54	0.50	26.27	26.53^{c}	26.40^{c}
2	0	10.88^{c}	11.50^{b}	11.19^{c}	1.42^{de}	1.48	1.45^{de}	0.24	0.28	0.27	25.41	25.57^{cd}	25.49^{c}
	3	11.50^{bc}	12.14^{b}	11.82^{b}	1.80^{b}	1.88	1.84^{b}	0.36	0.40	0.38	28.83	29.07^{b}	28.95^{b}
	6	12.45^{a}	13.12^{a}	12.78^{a}	2.14^{a}	2.22	2.18^{a}	0.53	0.62	0.57	31.92	32.25^{a}	32.09^{a}
P-value		0.015	0.044	0.023	0.026	0.095	0.050	0.073	0.054	0.238	0.062	0.044	0.048
CV (%)		3.61	3.45	3.32	4.15	4.27	4.03	6.10	6.07	6.05	4.18	4.10	4.06

CV= coefficient of variation. Means followed by the same letters within a column are not significantly different at $p < 0.05$, based on Tukey's test.

Overall, results showed that the reduction of exchangeable acidity, exchangeable Al^{3+} and increment of nutrients availability with the application of lime and compost were better in the later experimental season.

The result is in line with the findings of Rheinheimer et al. (2018) and Li et al. (2014), who found that lime application increased soil pH, reduced exchangeable acidity and exchangeable Al^{3+} and thereby improved available plant nutrients steadily. On the contrary, our result contradicts with findings of Peter et al. (2014), who found that liming increased soil pH, while exchangeable acidity and Al^{3+} were reduced during the first experimental year than the residual effect. The disparity between the present study results and the previous findings can be ascribed to variation in the purity of liming material, particle size, dose and time of application, inherent soil characteristics, and climatic conditions.

Effects of combined use of compost and lime on wheat growth and yield attributes

Results showed that the application of lime and compost in combination significantly ($p<0.05$) affected plant height, spike length and grains spike^{-1} of wheat (Table 6). However, plant height and spike length were not significantly influenced by the application of sole lime rates.

The average results indicated that the highest plant height (121.07 cm), spike length (12.14 cm) and grains spike^{-1} (69.96) were obtained from treatments that received 2 t ha^{-1} lime and 6 t ha^{-1} compost in combination, while the lowest values were recorded from the control. Plots amended with 1 t ha^{-1} lime combined with 3 t ha^{-1} compost increased plant height, spike length and grain spike^{-1} by 12.8, 22.7 and 48.5%, respectively, compared to the control. Besides, plant height, spike length and grain spike^{-1} were 26.8, 58, and 82.8% higher, respectively, under combined addition of 2 t ha^{-1} lime and 6 t ha^{-1} compost compared to the control.

Table 6 Effects of combined applications of lime and compost on growth characteristics of wheat

Lime (t ha^{-1})	Compost (t ha^{-1})	Plant height (cm)			Spike length (cm)			Grain spike^{-1}		
		2018	2019	Average	2018	2019	Average	2018	2019	Average
0	0	96.15^{d}	94.82^{f}	95.49^{f}	7.76^{d}	7.60^{g}	7.68^{e}	38.38	38.17^{g}	38.27^{g}
	3	100.54^{cd}	103.25^{de}	101.90^{de}	8.44^{d}	8.83^{de}	8.65^{d}	49.16	53.05^{de}	51.11^{de}
	6	103.52^{c}	105.93^{cd}	104.73^{cd}	9.65^{c}	9.81^{c}	9.73^{c}	53.18	56.10^{cd}	54.64^{cd}
1	0	96.48^{d}	99.10^{e}	97.80^{ef}	7.80^{d}	8.03^{fg}	7.90^{de}	41.87	44.70^{f}	43.29^{f}
	3	105.16^{c}	109.61^{c}	107.39^{c}	9.30^{c}	9.57^{cd}	9.43^{c}	54.89	58.73^{c}	56.81^{c}
	6	110.98^{b}	114.67^{b}	112.83^{b}	10.50^{b}	10.94^{b}	10.72^{b}	64.02	66.59^{b}	65.30^{b}
2	0	98.23^{d}	101.58^{e}	99.91^{ef}	8.19^{d}	8.48^{ef}	8.34^{de}	47.14	49.85^{e}	48.50^{e}
	3	112.42^{b}	115.78^{b}	114.17^{b}	9.47^{c}	9.90^{c}	9.68^{c}	56.70	59.80^{c}	58.25^{c}
	6	119.29^{a}	122.85^{a}	121.07^{a}	11.98^{a}	12.30^{a}	12.14^{a}	67.80	72.12^{a}	69.96^{a}
P-value		0.012	0.041	0.019	0.022	0.047	0.029	0.051	0.045	0.043
CV (%)		2.73	2.30	2.47	5.02	4.66	4.74	4.37	4.23	4.08

CV= coefficient of variation**.** Means followed by the same letters within a column are not significantly different at $p < 0.05$, based on Tukey's test.

Our results depicted that wheat's growth and yields performed better in 2019 than the 2018 cropping season, which could be as lime and compost may decompose and release nutrients slowly (Rheinheimer et al. 2018). The greater increment of plant height, spike length and grains spike^{-1} of wheat from combined treatments could be related to reduced soil acidity and increased availability of nutrients that may enhance vegetative growth (Melese et al. 2015). In addition, the application of compost alone or combined with mineral fertilizers improved soil bulk density and water holding capacity, resulting in better roots growth and nutrients use efficiency (Agegnehu et al. 2016). Our result is in line with Demissie et al. (2017), who indicated that the addition of organic and inorganic fertilizers together provided the highest plant height. Similarly, Ali et al. (2020) showed that combined use of fertilizers enhanced plant height which could be related to better supply and uptake of nutrients for cell division, and expansion leads to better vegetative growth. Lime and compost additions in conjunction showed a significant ($p<0.05$) effect on biomass and grain yields of wheat (Table 7). But the straw yield was not significantly ($p>0.05$) affected by sole and combined treatments. The average results of the two cropping seasons showed that the application of 2 t ha^{-1} lime combined with 6 t ha^{-1} compost gave the highest biomass, grain and straw yields of wheat (12.53, 5.22 and 7.31 t ha^{-1}), respectively. Plots treated with 2 t ha^{-1} lime, 6 t ha^{-1} compost in isolation and their combinations increased dry wheat biomass by 14.5, 24, and 60.1%, respectively, compared to the control. Similarly, treatments that received 2 t ha^{-1} lime, 6 t ha^{-1} compost alone and their combination increased grain yield by 24.2, 41.8 and 96.9%, respectively, compared to the control. In addition, biomass and grain yields were higher by 29.3 and 54.3%, respectively, due to the application of 1 t ha^{-1} lime and 3 t ha^{-1} compost in conjunction compared with the control treatment.

Table 7 Effects of lime and compost application on yield and yield components of wheat

Lime	Compost	Biomass yield (t ha^{-1})			Grain yield (t ha^{-1})			Straw yield (t ha^{-1})		
(t ha^{-1})	(t ha^{-1})	2018	2019	Average	2018	2019	Average	2018	2019	Average
0	0	7.94^{g}	7.72^{h}	7.83^{g}	2.70^{h}	2.59^{g}	2.65^{f}	5.25	5.13	5.18
	3	8.94^{de}	9.37^{ef}	9.15^{de}	3.34^{ef}	3.48^{e}	3.41^{e}	5.60	5.89	5.74
	6	9.52^{cd}	9.90^{de}	9.71^{cd}	3.65^{de}	3.86^{d}	3.76^{d}	5.87	6.41	5.95
1	0	8.21^{fg}	8.62^{g}	8.41^{fg}	2.91^{gh}	3.03^{f}	2.96^{f}	5.30	5.59	5.45
	3	9.91^{c}	10.34^{d}	10.12^{c}	3.98^{cd}	4.19^{c}	4.09^{c}	5.92	6.15	6.03
	6	11.72^{a}	12.27^{b}	11.99^{a}	4.62^{b}	4.85^{b}	4.73^{b}	7.10	7.42	7.26
2	0	8.79^{ef}	9.13^{fg}	8.96^{ef}	3.22^{fg}	3.35^{e}	3.29^{e}	5.57	5.78	5.67
	3	10.90^{b}	11.20^{c}	11.04^{b}	4.31^{bc}	4.46^{c}	4.40^{c}	6.59	6.74	6.64
	6	12.19^{a}	12.88^{a}	12.53^{a}	5.13^{a}	5.30^{a}	5.22^{a}	7.06	7.58	7.31
P-value		0.005	0.003	0.003	0.011	0.046	0.014	0.079	0.104	0.081
CV (%)		4.15	3.29	3.51	5.38	4.73	4.72	6.19	6.01	5.77

CV= coefficient of variation**.** Means followed by the same letters within a column are not significantly different at $p < 0.05$, based on Tukey's test.

Results showed that the application of lime and compost in combination noticeably increased wheat yield and yield attributes compared to sole applications and the control, which could be associated with increased soil pH, reduced exchangeable Al^{3+} and increased levels of plant nutrients (Vishwanath et al. 2020). Besides, the integrated use of organic and inorganic fertilizers increased crop yields related to greater soil organic matter content, better mineralization, and the release of available nutrients (Mamuye et al. 2021; Jiangzhou et al. 2020). For instance, Helgason et al. (2007) revealed that the application of compost increased N uptake by 27-99% compared to the control. Ali et al. (2018) also reported that combined nutrient management enhances soil structure and water holding capacity, improving nutrient uptake and crop yields. In agreement with our result, Singh et al. (2017) showed that biomass and grain yields were 51.42% and 57.34%, respectively, higher by integrating mineral fertilizers and lime over sole mineral fertilizer application. Agegnehu et al. (2014) also noted that the grain yield of wheat was 151% higher from the application of 60/20 kg N/P ha^{-1} along with 50% manure and compost compared to the control.

Economic analysis

The results of the cost-benefit analysis showed that applying 2 t ha^{-1} lime and 6 t ha^{-1} compost in combination gave the highest net profit (1915.89 US$ ha^{-1}), followed by treatments that received combined rates of 1 t ha^{-1} lime and 6 t ha^{-1} compost (1782.57 US$ ha^{-1}) (Table 8). In contrast, the minimum net benefit (1034.44 US$ ha^{-1}) was achieved from untreated control plots followed by the application of 1 and 2 t ha^{-1} lime (1104.95 and 1181.83 US$ ha^{-1}, respectively). Results showed that the application of lime alone provided less profit as it provided lower grain yield and net benefit but greater variable cost. On the other hand, the highest net benefit gained in plots amended with compost and lime in conjunction could be related to improved soil fertility and wheat yields.

Table 8 Partial budget analysis of compost and lime combination for wheat production

Lime ($t\ ha^{-1}$)	Compost ($t\ ha^{-1}$)	TVC ($US\$\ ha^{-1}$)	GY ($kg\ ha^{-1}$)	SY ($kg\ ha^{-1}$)	GB ($US\$\ ha^{-1}$)	NB ($US\$\ ha^{-1}$)	MRR (%)
0	0	91.76	2385	4662	1126.2	1034.44	
	3	109.31	3069	5166	1427.03	1317.72	1613.82
	6	126.86	3384	5355	1564.42	1437.56	682.73
1	0	144.95	2664	4905	1249.9	1104.95 D	-
	3	162.50	3681	5427	1691.14	1528.64	2413.73
	6	180.05	4257	6534	1962.62	1782.57	1446.64
2	0	198.14	2961	5103	1379.97	1181.83 D	-
	3	215.69	3960	5985	1823.22	1607.53	2425.18
	6	233.24	4698	6579	2149.13	1915.89	1756.73

1US$ = 36.7ETB (Ethiopian birr). TVC= total variable cost; GY= grain yield; SY= straw yield; GB= gross benefits; NB= net benefits; D= dominance; MRR= marginal rate of return.

Conclusion

The present study showed that the application of lime and compost reduced soil acidity, increased soil nutrient contents and crop yields compared to the control. However, adding lime and compost separatly did not maintain the desired soil pH, exchangeable aluminium, soil nutrients, and wheat yields. Overall, the combined addition of compost and lime at lower rates substantially increased soil pH, soil organic carbon, total nitrogen, available phosphorus and exchangeable bases.

In contrast, exchangeable acidity and aluminum levels noticeably decreased compared to their separate additions. Besides, the highest biomass, grain yield and income were obtained from the integrated addition of treatments. Based on the findings, we concluded that applying 2 t ha^{-1} lime and 6 t ha^{-1} compost combined with 75 kg ha^{-1} blend NPSB and 150 kg ha^{-1} urea fertilizers could be the best management option to mitigate soil acidity, improve nutrients status and crop yield at a lower cost. However, to determine the application frequency, the long-term effects of lime and compost in combination on soil acidity and crop yield need to be investigated through further research.

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Compliance with ethical standards

Conflict of interest The authors declare that there are no conflicts of interest associated with this study.

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